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A PRELIMINARY INVESTIGATION OF THE INTEGRATION OF MODELLED FLOODPLAIN HYDRAULICS WITH ESTIMATES OF OVERBANK FLOODPLAIN SEDIMENTATION DERIVED FROM Pb-210 and Cs-137 MEASUREMENTS

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ABSTRACT

This paper investigates the possibility of linking finite element modelled two-dimensional hydraulics with floodplain sedimentation rates derived from radionuclide dating techniques. The TELEMAC-2D system is used to simulate the full dynamic velocity vector and water depth distributions for a 1 in 12 year flood event for the River Culm, Devon. These are compared to patterns of medium-term (30–100 years) sedimentation rates and a degree of correlation is found to exist. This information is used to comment on the complexity of flow and sediment deposition interactions in floodplain environments and to provide a research design for the development of a more fully integrated floodplain morphodynamic model. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS floodplain sedimentation; hydraulic modelling; radionuclide dating

INTRODUCTION

River floodplains have attracted increasing attention in recent years (Anderson *et al*., 1996). This interest reflects, at least in part, the ecological significance of floodplains and river corridors within the landscape, their importance as a buffer between the river and the surrounding land, and their role in providing storage for flood control. There is also a growing awareness of their potential significance as sinks and stores for river-borne sediment and associated nutrients and contaminants. Because of their dynamic nature, sediment deposited on river floodplains may be reworked in the future and may thus also constitute a problem for future river management (Leenaers and Schouten, 1989). Against this background there is clearly a need for an improved understanding of the geomorphological evolution of floodplains and their role as sediment sources and sinks.

In considering the geomorphological evolution of floodplains, attention is commonly directed either to the coarse channel deposits and the interaction between channel migration and floodplain construction and destruction (Wolman and Leopold, 1957; Howard, 1992) or to the fine overbank deposits which mantle large areas of most floodplains and result in vertical accretion of the floodplain surface. The former have been most frequently studied, because for most 'active' rivers channel migration provides clear visual evidence of floodplain evolution and change. The slow rates of accretion associated with overbank deposition are less readily documented and afford less tangible evidence of floodplain development. However, for many lowland river floodplains, particulary those where channelization and river training works limit or prevent channel migration, the overbank deposition of fine sediment will represent the dominant component of floodplain evolution. In order to develop an improved understanding of this important aspect of floodplain development, more information on rates and patterns of overbank sediment deposition is required.

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Approaches to the investigation of rates and patterns of overbank deposition can involve a range of temporal scales. Sediment deposition associated with individual events can be documented (e.g. Asselmann and Middelkoop, 1995) and such work can provide valuable insights into the relationship between sedimentation rates and floodplain characteristics, flow patterns, suspended sediment concentrations and the surface conditions of the floodplain. Equally, on a longer timescale, identification of datable horizons (e.g. Costa, 1975; Lewin and Macklin, 1987) can afford useful insights into floodplain evolution. Problems may, however, arise in matching the timescale to the precise needs of a study. Thus, although an event-based approach may be needed to take account of the complex interaction of inundating floodwater and floodplain topography, a long-term perspective will also be necessary when considering, for example, floodplain evolution, the feedback between the changing microtopography of a floodplain produced by spatial variation in deposition rates, and future sedimentation patterns and the long-term fate of sediment-associated contaminants deposited within the floodplain system. Furthermore, magnitude and frequency considerations will inevitably mean that any conclusions based on short-term event-based monitoring may not provide representative information on the key controls of floodplain evolution.

Such integration of event-based and longer-term perspectives is clearly difficult to achieve within the framework of a field monitoring programme of finite duration. In addition, there is frequently a need to extrapolate the findings of field measurement programmes to larger areas. Scope therefore undoubtedly exists to broaden both temporal and spatial perspectives by combining field observation with distributed numerical models of floodplain behaviour that are capable of simulating the detailed response of individual flood events along river reaches for a range of events. Any attempt to link both event-based and longer-term perspectives through the use of models will, however, need to take account of changing boundary conditions which could confound attempts to link these different timescales. For this reason a temporally constrained, medium-term approach is likely to prove the most meaningful and productive for an initial investigation.

This paper thus explores the potential for such a linkage between hydraulic model predictions of flood inundation and velocities, and estimates of medium-term floodplain sedimentation rates. Field and modelling techniques are outlined, and the results of field measurements and spatially distributed model predictions compared. Both techniques are seen to be constrained by limitations of expense and computer power, emphasizing the potential power of a fully integrated model.

Recent developments in hydraulic modelling

Until relatively recently the standard approach to modelling free surface flows in compound channels has been a one-dimensional finite difference representation (Samuels, 1990). However, large-scale flume studies (e.g. Knight and Shiono, 1993; Sellin and Willetts, 1996) have begun to demonstrate the importance of such mechanisms as momentum transfer between main channel and floodplain flows and flow across meander loops in compound channels. These studies have indicated that while in-channel flows may be satisfactorily described by a one-dimensional representation, out-of-bank flows incorporate significant three-dimensional effects which invalidate this class of model (Knight and Shiono, 1996). To meet this need to develop higher dimensional models, computational fluid dynamics (CFD) techniques have been imported into the Earth sciences from engineering and mathematics. However, despite their availability since the early 1970s (e.g. King and Norton, 1978), application to complex problems such as river flooding has awaited sufficient computer power and the development of stable algorithms to simulate dynamically moving inundation extent boundaries (Hervouet and Janin, 1994). The latter have recently become available and the last decade has seen the development of a number of two-dimensional, or higher, models for flood inundation problems (see Bates *et al.*, 1997) for a review). Such schemes solve either the Shallow Water or Navier–Stokes equations for a series of nodal points on either a finite difference or finite element mesh to predict spatial patterns of water depth and flow velocity throughout dynamic flood events.

Recent developments in documenting medium-term floodplain sedimentation rates

Existing approaches to documenting rates of overbank sedimentation on river floodplains have included the use of sedimentation traps (e.g. Gretener and Strömquist, 1987; Lambert and Walling, 1987; Asselmann and Middelkoop, 1995), post-event surveys of the deposits resulting from individual floods (e.g. Brown, 1983; Marriott, 1992) and the identification of datable levels within the overbank deposits (e.g. Trimble, 1983; Hupp, 1988; Lewin and Macklin, 1987). The first two approaches are primarily applicable to individual events, although such results can be summed to provide data for longer periods. However, the use of sedimentation traps faces problems of representativeness and the need to deploy the traps in advance of the flood event, as well as practical constraints on sampling density, whilst post-event surveys are heavily reliant upon the existence of measurable depths of sediment and of a clearly defined interface between the 'new' sediment and the original surface. The use of datable levels or surfaces to estimate sedimentation rates will, by definition, provide longer-term average values which will integrate inter-event variability conditioned by such factors as flood magnitude and duration and suspended sediment concentrations. However, the viability of this approach is ultimately dependent upon the ability to establish datable levels and the lack of temporal resolution may prove problematical where long timescales and consequently changing sedimentation rates are involved.

Recent advances in the application of environmental radionuclides, and more particularly the fallout radionuclides caesium-137 (Cs-137) and unsupported lead-210 (Pb-210), to documenting rates and patterns of floodplain sedimentation can be viewed as an extension of this latter approach, wherein down-profile variations in the concentrations of these radionuclides can provide a basis for establishing the recent chronology of overbank sediment deposition, and measurements of total radionuclide inventories can be used to estimate average sedimentation rates (Walling and He, 1993, 1994, 1997; He and Walling, 1996; Walling *et al.*, 1996). Use of fallout radionuclides in this context affords many advantages over other methods for documenting overbank floodplain sedimentation, including the general applicability of the approach to a wide range of environments and locations, the medium-term timescales involved (*c.* 40 years for Cs-137 and *c.* 100 years for unsupported Pb-210) and the potential for assembling data for a large number of points on a floodplain and thereby for investigating the spatial variability of deposition rates and the patterns involved.

Detailed consideration of the basis for using Cs-137 and unsupported Pb-210 measurements to estimate rates of overbank sedimentation on river floodplains lies beyond the scope of this paper and the reader is referred to He and Walling (1996), Walling and He (1993, 1994, 1997) and Walling *et al.* (1996) for further details of the approach. In essence, it exploits the fact that Cs-137 and unsupported Pb-210 accumulate within accreting overbank sediment deposits as a result of both direct atmospheric fallout to the floodplain surface and deposition of suspended sediment. The latter represents material mobilized from the upstream catchment by erosion which will also contain Cs-137 and unsupported Pb-210 originally deposited as fallout on the catchment surface. Both the total inventory or amount of the radionuclide contained in a floodplain sediment profile and its vertical distribution will therefore differ from that of a natural undisturbed soil above the level of flood inundation, which will only receive inputs associated with direct atmospheric fallout and which will be characterized by a stable non-accreting surface.

Cs-137 is an artificial fallout radionuclide with a half-life of 30·17 years which was introduced into the environment by the atmospheric testing of thermonuclear weapons primarily during the late 1950s and the 1960s. The depth distribution of the radionuclide in the floodplain sediment, therefore, reflects the temporal pattern of fallout. The peak Cs-137 activity can thus be ascribed to 1963, the time of maximum fallout, and the dating of this level provides a means of estimating the average sedimentation rate over the past *c.* 30 years. Comparison of the total Cs-137 inventory for a floodplain core with those of adjacent natural undisturbed soils, in order to establish the excess inventory associated with sediment deposition, provides an alternative means of estimating the average sedimentation rate over the period since the onset of significant caesium fallout (i.e. since *c.* 1954). In the latter case, only a single measurement of the total inventory of the bulk core is required, rather than measurements of the

individual sections of the core needed to define the depth distribution of Cs-137, although it is necessary to take account of variations in grain size composition between individual floodplain cores. Because of the time-consuming nature of Cs-137 measurements, use of whole-core inventory values to estimate sedimentation rates provides greater scope for assembling information for a large number of points on the floodplain, thereby enabling the investigation of spatial patterns of sedimentation.

Although unsupported Pb-210 is also a fallout radionuclide, it differs from Cs-137 in two important respects. First, it is of natural origin, representing a product of the U-238 decay series with a half-life of 22·26 years. Second, because of its natural origin, the annual fallout may be viewed as being essentially constant through time. It therefore affords a means of estimating deposition rates over somewhat longer time periods (i.e. 50–150 years). Information on the vertical distribution of unsupported Pb-210 concentrations in overbank floodplain sediments can again be used to date specific levels and thereby estimate deposition rates, but He and Walling (1996) have also demonstrated how a single measurement of the total unsupported Pb-210 inventory for a bulk sediment core can be used to estimate the average rate of accretion at the point where the core was collected. As in the case of Cs-137, it is necessary to compare the total inventory of the floodplain core with those of representative cores from adjacent undisturbed areas above the level of flood inundation, in order to calculate the excess unsupported Pb-210 deposited in association with overbank sediments, and to take account of variations in grain size composition between individual cores. Again, use of single bulk core measurements affords potential for estimating deposition rates for a large number of points on a floodplain which can be used to document spatial patterns.

The application of Cs-137 and unsupported Pb-210 measurements to documenting spatial patterns of floodplain accretion will in most cases be constrained either by the number of cores that can be collected or by the laboratory analysis required to determine the total Cs-137 or unsupported Pb-210 inventory of the cores or to establish the vertical profiles of the radionuclide in the core. In the former case, use of a motorized percussion corer or similar powered equipment can facilitate the collection of a large number of cores in order to investigate spatial patterns of floodplain sedimentation, but laboratory capacity for gamma-spectrometry analysis will frequently limit the number of whole cores or sectioned cores that can be analysed. Count times are typically of the order of 50000 s or more for each sample analysed and, even if the detector is fully committed to such analyses, only a limited number of cores can be processed. This will necessitate careful planning of the sampling programme aimed at obtaining cores from a floodplain, in order to optimize the spatial resolution provided by a given number of cores. Where suitable facilities exist, both Cs-137 and unsupported Pb-210 activities can, however, be measured simultaneously for the same sample.

Integration potential

The aim of this paper is to investigate possibilities for linking event-based hydraulic model output to medium-term deposition rates derived from analysis of radionuclide measurements. The site selected is a region on the floodplain of the River Culm in Devon (e.g. Walling and He, 1993; He and Walling, 1996; Walling *et al.*, 1996). The feasibility of developing a linkage relies firstly on the confidence in the Cs-137/Pb-210 derived estimates of medium-term sedimentation rates, as well as the ability to satisfactorily simulate hydraulically complex floodplain flows. Second, it is necessary to establish a stability of process over the medium term, which would indicate the potential for a more detailed integration of event-based to medium-term estimates of sedimentation rates. Such a 'stability' could represent itself, for example, in the repeatability of hydraulic patterns predicted for a certain range of flood magnitudes.

Two approaches to investigating rates of overbank sediment deposition are presented in this paper. Using Pb-210 and Cs-137 measurements on floodplain cores, it is possible to obtain estimates of medium-term floodplain sedimentation rates resulting from a set of flood events of varying magnitude. The fieldwork involved is labour intensive with regards to the spatial extent of data required. However, from one sample it is possible, in theory, to obtain a spatially discrete, but temporally lumped estimate of overbank deposition for, in the case of Cs-137, *c.* 40 years, and in the case of Pb-210, *c.* 100 years

(Walling and He, 1993; He and Walling, 1996).

At the same time, finite element simulations of single flood events are able to produce an areally extensive prediction of floodplain inundation and hydraulic parameters (e.g. Bates *et al*., 1992, 1994, 1996). As overbank sedimentation is controlled by the hydraulic regime of the flood, it should be possible to obtain a spatial distribution of parameters such as flow velocity and depth, which drive the relative patterns of deposition and scour on the floodplain throughout an event. In the present study, evolution of the floodplain topographic boundary condition is not implemented due to the low rates of landform change (maximum deposition at this site is always $< 1{\cdot}0\,g\,cm^{-2}\,a^{-1}$). As even a single event may take up to three days to model using a high specification workstation, simulation of time periods sufficient to undergo significant topographic change is currently prohibited when using two-dimensional finite element methods.

This, therefore, is a preliminary investigation into the current research gap between our knowledge of event-based hydraulics and the floodplain landforms that evolve over the medium term as a result of such processes. As a consequence of this we also wish to examine the feasibility of developing an integrated hydraulic/morphological evolution model. Unlike the present study, this would ultimately require an evolution of the floodplain topography boundary condition over time coupled to a change in the hydraulic patterns that result in order to encompass complex feedback. Such a model would allow prediction of medium-term sedimentation rates over a wider spatial scale than would otherwise be possible, resulting in a minimization of the expense of collecting field data in terms of time and analytical cost.

RESEARCH DESIGN

The study reach

In the present study, attention is focused on an 11 km reach of the River Culm floodplain between the gauging stations at Woodmill (upstream) and Rewe (downstream) (Figure 1c). At the outlet of this reach the river drains a catchment area of *c*. $276\,km^2$. The mean annual precipitation and runoff for the catchment are estimated to be *c*. 925 mm and 510 mm, respectively, and the mean annual flood at the Woodmill gauging station located at the head of the reach has been estimated to be *c*. $80\,m^3\,s^{-1}$. Within this reach the river meanders across a well-developed floodplain which averages about 450 m in width and occupies a gravel-bed channel which is approximately 12 m wide. The banks are up to 1 m high and are largely cut into fine alluvial material. Overbank flooding during the winter months is relatively frequent and substantial inundation of this floodplain typically occurs on about eight to ten occasions per year. Depth of inundation varies according to the local topography of the floodplain, but in the middle reaches floodwater depths are typically about 40 cm for the mean annual flood and *c*. 70 cm for a 50 year flood. Land use on the floodplain is almost exclusively permanent pasture. The mean annual specific suspended sediment yield of the basin has been estimated to be *c*. $32\,t\,km^{-2}\,a^{-1}$ and peak suspended sediment concentrations during flood events are typically in the range 400–800 $mg\,l^{-1}$. The suspended sediment load of the river is also notable for its fine-grained composition (Walling and Moorehead, 1989) with a d_{50} averaging 6·5 μm. Previous work undertaken on this floodplain reach has indicated that approximately 28 per cent of the annual sediment load entering the reach may be deposited on the floodplain during overbank events (Walling and Bradley, 1989). Such conveyance losses are equivalent to an average accretion rate for overbank sediment of *c*. $500\,g\,m^{-2}\,a^{-1}$ ($0{\cdot}5\,mm\,a^{-1}$) and confirm the suitability of the reach for studying floodplain sedimentation patterns.

Within the 11 km reach, particular attention was focused on a short stretch of the floodplain near Silverton Mill (Figure 1a) where overbank inundation was a frequent occurrence during flood events. This location affords a representative range of floodplain features and topography. More particularly it comprises a depression within a meander bend, bordered by an elevated bank margin or natural levee and a linear depression along the outer margin of the floodplain. Flow through this section has a complex structure, and therefore provides a robust test for the hydraulic model.

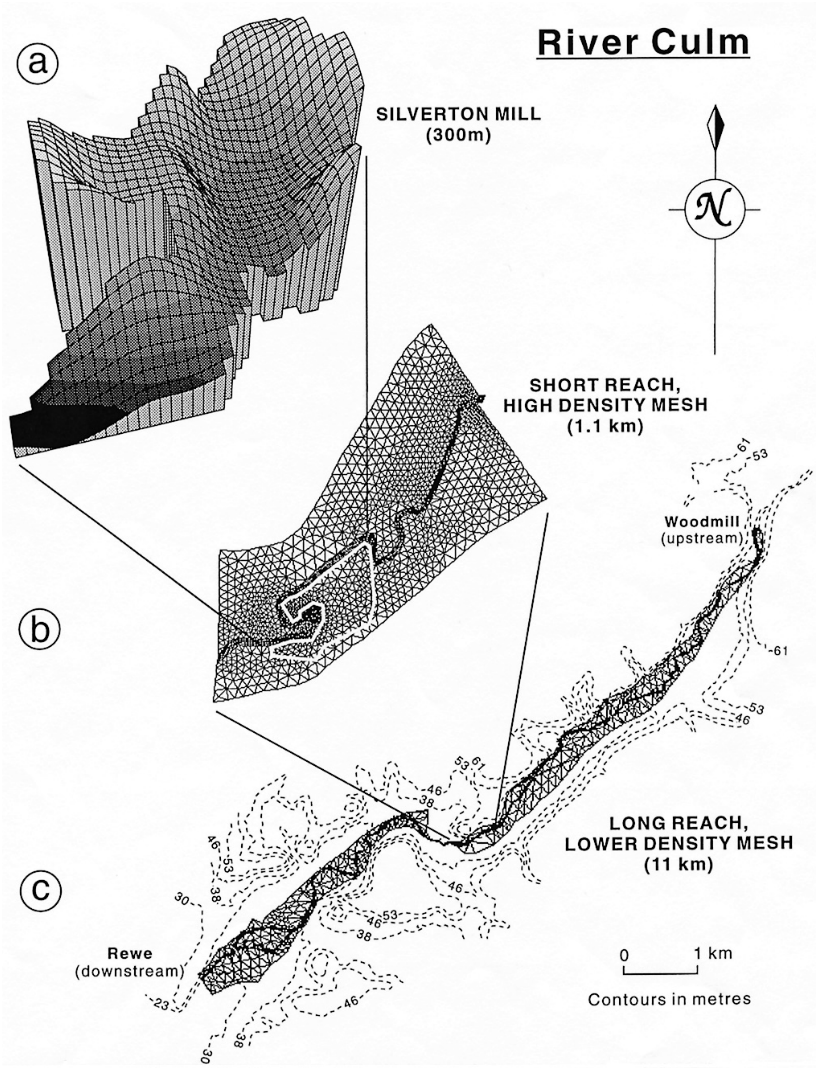


Figure 1. (a) Pb-210 and Cs-137 surveyed zone at Silverton Mill. (b) Short reach, high density finite element mesh of the River Culm. (c) Long reach, lower density finite element mesh of the River Culm

Obtaining the spatial pattern of medium-term sedimentation rates

Within the area of the floodplain near Silverton Mill selected for detailed investigation, bulk sediment cores were collected from the floodplain using a motorized percussion corer equipped with a 6·9cm diameter core tube. A small sample was collected from the base of each core for subsequent radionuclide assay, in order to ensure that the core had penetrated to the full depth of the Cs-137 and unsupported Pb-210 profiles. In total, 274 sediment cores were collected from the study area based on a 12m grid. Samples of surface sediment were also collected from a point immediately adjacent to each core for grain size analysis. Where sectioned cores were required, a larger 12cm diameter core tube was employed and the sediment core was sectioned into 1 or 2cm depth increments after extrusion. Suspended sediment samples were collected from the river during flood events over a period of two years. Samples of sediment deposited on the floodplain during overbank flows were also collected using sediment traps installed at various locations prior to flood events and retrieved immediately after the flood receded. In addition, soil cores from nearby undisturbed permanent pasture fields above the floodplain inundation

level were collected for analysis to establish the local fallout Cs-137 and Pb-210 reference inventories. A detailed topographic survey consisting of 950 points was also undertaken in parallel with the coring programme, using an electronic theodolite.

All bulk cores and other samples were air-dried, ground and homogenized prior to measurement of their Cs-137 and unsupported Pb-210 content by gamma spectrometry. The measurements were undertaken using a high resolution, low background, low energy, n-type coaxial HPGe detector, which permitted simultaneous measurements of both radionuclides. In order to permit measurement of Pb-210, samples were sealed for 20 days before gamma assay in order to ensure equilibrium between Ra-226 and Rn-222. Values of unsupported Pb-210 activity were derived from measurements of the total Pb-210 activity by subtracting the Ra-226 supported Pb-210 activity (Joshi, 1987). The Ra-226 activity in the sample was estimated from the measured activity of its short-lived daughter Pb-214 which is also in equilibrium with Ra-226. Cs-137 concentrations were obtained by measuring the activity at 662 Kev. Count times were typically *c.* 10h and produced values of both unsupported Pb-210 and Cs-137 activities with a precision of *c.* ± 10 per cent at the 90 per cent level of confidence. Measurements of the grain size composition of samples were undertaken using laser diffraction apparatus (Malvern Mastersizer), after appropriate pretreatment.

The excess Cs-137 and unsupported Pb-120 inventories (total inventories less local reference inventories) associated with the individual floodplain sediment cores were used to derive estimates of the mean annual sedimentation rate for the sampling points using the bulk core procedures described by Walling and He (1997) and He and Walling (1996), respectively. In the case of the sedimentation rates derived from the Cs-137 measurements, the values obtained represent average values for the period since the commencement of significant caesium fallout in the mid-1950s (i.e. *c.* 40 years). The values derived from the unsupported Pb-210 measurements represent average values for a longer period (i.e. *c.* 100 years).

The two-dimensional finite element hydraulic model

Depth-averaged calculations of river hydraulics were based on the TELEMAC-2D two-dimensional finite element model (Hervouet, 1989, 1993) adapted specifically for long reach floodplain studies (Bates *et al.*, 1994, 1995). Specific modifications included a method to simulate flow over partially wet elements, new numerical algorithms particularly suited to floodplain finite element discretizations, and improvements to the mass conservation properties of the model for this class of application (Bates *et al.*, 1994). Previous modelling studies at this site (Nicholas and Walling, 1995) have been restricted to steady-state hydraulics and finite difference solution techniques using a 5m nodal spacing in order to allow a coupled hydraulic/sediment transport model to be applied. Here we take the alternative, but complementary, view that it is essential to optimize the hydraulic representation, prior to using this to drive sediment transport calculations. The approach taken therefore includes convective acceleration terms in order to treat the problem as fully dynamic and uses the computationally more demanding finite element method to enable better representation of a meandering channel within a wider floodplain belt at the expense of omitting coupled sediment transport calculations.

The model thus solves the second-order partial differential equations for depth-averaged fluid flow derived from the full three-dimensional Navier–Stokes equations. This gives an equation set consisting of an equation for mass continuity and two force–momentum equations. These equations, called the Shallow Water or Saint-Venant equations, are given in non-conservative form as:

$$\frac{\partial h}{\partial t} + \mathbf{u}.\mathbf{grad}(h) + (h\mathrm{div}(\mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + \mathbf{u}.\mathbf{grad}(u) + g\frac{\partial h}{\partial x} - \frac{1}{h}\mathrm{div}(v_t\ h\mathbf{grad}(u)) = S_x - g\frac{\partial Z_f}{\partial x} \tag{2}$$

$$\frac{\partial v}{\partial t} + \mathbf{u}.\mathbf{grad}(u) + g\frac{\partial h}{\partial y} - \frac{1}{h}\mathrm{div}(v_t\, h\mathbf{grad}(v)) = S_y - g\frac{\partial Z_f}{\partial y} \tag{3}$$

where u and v are the velocity components in the x and y Cartesian directions, $\mathbf{u}$ is the velocity vector, h is the depth of flow, Z_f is the bed elevation, v_t is the turbulent viscosity, S_x and S_y are the source terns, g is the gravitational acceleration and t is the time.

The model therefore solves for the three unknowns u, v and h, with turbulence treated using a constant effective viscosity throughout the domain. This combines the effects of molecular viscosity, turbulent viscosity and dispersion represented in a single velocity diffusivity term with units $m^2\ s^{-1}$. Thus, a larger velocity diffusivity term results in the dissipation of larger eddies, and hence mesh size is a significant factor in parameter selection as a velocity diffusivity resulting in dispersion of eddies less than two mesh elements in size will have virtually no effect on the computation. In terms of this study the requirement to model at reach scales led to minimum element sizes in near-channel areas of approximately 5m and a time step of 4s. Hence, the model will be insensitive to velocity diffusivity values less than $1{\cdot}1\,m^2\ s^{-1}$ and, accordingly, a value of 2·0 was selected. The constraint on grid size for reach-scale simulations therefore effectively limits the model to simulation of eddy length scales greater than 10m, even when a dimensional analysis (Hervouet and Van Haren, 1996) of fluvial flow indicates a Kolmogorov length scale (the size of the smallest eddies present) of 0·03mm! Ultimately, however, models will be required that overcome the current need to employ such simple turbulence closure schemes in reach-scale models. This will require solutions that are better able to account for the impact of the smallest eddies on the overall flow field and which can simulate larger-scale transient turbulence effects in the shear layer between main channel and floodplain flows.

Closure of this initial value–boundary value problem was achieved by specification of inflows and outflows to the computational domain and the provision of an initial estimate of water depth and velocity at each computational node. Friction was defined as a quadratic function of velocity with the resolved components of the bottom friction force being added to the momentum equations (Equations 2 and 3). The model also incorporates an additional modification to simulate areas of low lateral bed slope such as floodplains or tidal flats, which can be used to develop more realistic flow velocities in floodplain areas (see Bates *et al.*, 1997). A complete description of the solution of this equation set using the finite element method is provided by Hervouet and Van Haren (1996).

The Saint-Venant equations assume that vertical fluid acceleration is negligible, thus sudden changes of bottom topography are not represented by a corresponding component of vertical flow. The application of three-dimensional dynamic models is not yet feasible because of excessive computer cost (Van Rijn, 1993). Fortunately, Rodi *et al.* (1981) note that even in the presence of such three-dimensional effects, in many rivers the depth-averaging method may be sufficiently accurate for practical purposes. They do qualify this statement by saying this may only be true in regions with low topography and velocity gradients, which may cast doubt on the model representation of near-channel areas. However, Falconer and Chen (1996) conclude that in modelling floodplain processes, the depth of flow is generally small and the flow can be assumed to be well-mixed vertically. This allows the flow to be approximated by a two-dimensional horizontal flow formulation, which significantly reduces the computational cost, and allows the modelled spatial extent and resolution to be maximized. However, as with all model assumptions, depth-averaging does lead to a degree of uncertainty in the model formulation and merits further investigation.

Hydraulic model configuration

Two finite element meshes were set up for the river Culm. A large reach mesh (Figure 1c) approximately 11km in length, consisting of 2019 triangular elements, was set up with upstream and downstream boundary conditions obtained from data (15 min interval) taken from the Woodmill and Rewe gauging stations, respectively. Predictions from this model were used to provide the boundary

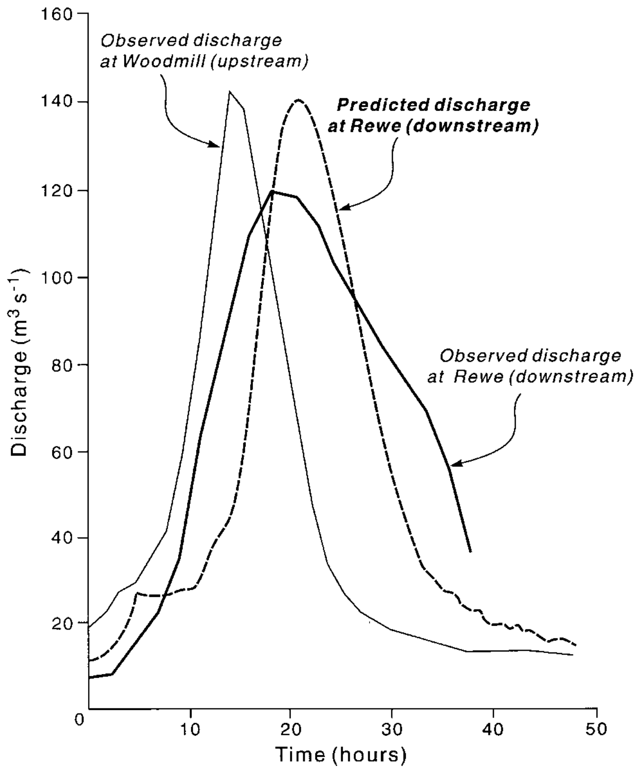


Figure 2. Input hydrograph at Woodmill and output hydrographs (modelled and observed) at Rewe for the one in 12 year event of December 1979

conditions for a smaller (*c.* 1km), higher resolution mesh with 3324 elements of the Silverton Mill site (Figure 1b). The topography for both meshes were taken from Ordnance Survey data, with the topography of the short reach, fine mesh being supported by the intensive ground survey carried out during sediment coring. Some information was lost during the interpolation of 950 surveyed height points onto the corresponding 219 mesh nodes falling within the surveyed area. Given the importance of microtopography in floodplain sedimentation processes (Walling *et al.*, 1992), this represents an area for future refinement.

The channel, due to computational constraints, was assumed trapezoidal along the length of the reach. Although this is the method used in most finite element floodplain flow modelling to date (e.g. Bates *et al.*, 1992, 1994, 1996), more detailed definition of the channel geometry, when computational resources allow, would result in a more accurate modelled location of channel breaching points, and better representation of the momentum exchange with floodplain flows.

Gauging station data from Woodmill and Rewe detailing stage and discharge for a 1 in 12 year event at Woodmill which occurred in December 1979, were provided by the Environment Agency and the University of Exeter. The input and output hydrographs are shown in Figure 2. In general, high frequency events are thought to be more significant for floodplain construction over the long term (Richards, 1982). This event, however, caused inundation of the entire floodplain at the flood peak, and provided a large range of inundation depths and velocities through time, sufficient to allow the simulation of the full range of flow conditions possible within the complex region of interest.

The models were run until a steady-state, bankfull solution was obtained, providing the initial conditions for the simulation of the 1 in 12 year event. The flood event was then simulated, with

calibration of the modelled outflow against the observed discharge at Rewe being achieved by adjusting values of floodplain and channel friction values to minimize the phase error between the observed and modelled flow peaks. This approach was chosen because the only item of model-independent observed flow data was the timing of the downstream discharge peak. Whilst water level and discharge data existed at the downstream gauge, the former were used as a model boundary condition and the latter were subject to additional uncertainties due to a rating equation transformation. As a consequence, only the timing of peak discharge at Rewe was accurately known and was independent of the model. This procedure has the advantage of providing a relatively robust test of the models as all other aspects of the hydrograph (volume, magnitude of peak, timing and speed of rise, timing and attenuation of recession) were allowed to vary freely. Initial values of Manning's n were selected from Chow (1959) as 0·05 for the floodplain and 0·04 for the channel. Final calibrated friction values were 0·08 and 0·03 for the floodplain and channel, respectively, resulting in the modelled outflow hydrograph shown in Figure 2. Despite the fact that friction values vary markedly in space over the floodplain due to vegetation changes, and in time during the flood event with changes in stage, typically available observed flow data are not sufficiently detailed to require such sophistication from the model. This lack of data is the driving force behind the use of a simple, time-invariant two-value calibration and also its main disadvantage as it will ultimately limit the performance that can be achieved. The hydrograph simulation results show the model able to simulate routing of the flood wave through the reach, although it fails to capture fully the observed attenuation. As a consequence, absolute velocity values predicted by the model may contain a degree of error, although they should be correct relative to one another, particularly for such a high magnitude flood event where the floodplain is fully inundated for a long period of time. However, it is important not to over-interpret such external validation (*cf.* Fawcett *et al.*, 1995), particularly where the model has been calibrated or where there may be uncertainty over the observed data. In this case, rating curves for out-of-bank flow are notoriously difficult to estimate accurately (see Ervine and Baird, 1982) and this may be a factor here. Having achieved a calibrated run on the long reach, coarse mesh, it was possible to extract the necessary boundary condition input and output hydrographs for the fine mesh. In the absence of gauged data for a river, this 'nested' meshing technique represents a powerful methodology, enabling high resolution analysis of a local site within the long reach, coarse mesh, while maintaining low computational cost.

Using the extracted boundary conditions from the calibrated long reach model, the event was re-run over the short reach, fine mesh, using an identical friction calibration to give predictions of water depth and velocity at each node and at each time-step.

INTEGRATION OF HYDRAULIC AND SEDIMENTOLOGICAL RESULTS

To facilitate direct comparison, the various data sets were interpolated onto the mesh nodal positions using an inverse distance weighting method. Accordingly, Figures 3, 4 and 5 show the spatial patterns of Cs-137 and Pb-210 derived medium-term sedimentation rates and the percentage of fine particles for this site overlaid onto the reach topography which provides the z co-ordinate for these diagrams. From physical principles one would expect the deposition of fine sediments to be hydraulically controlled. Build-up of fine sediment should thus occur in regions of low velocity or where long-term ponding is experienced. On the other hand, coarse sediments will be, to a greater extent, supply limited. Thus, one would expect coarse sediments to be deposited close to areas of sediment supply, in this case the channel, as the floodplain hydraulics are not able to maintain such material in suspension over long distances (see Marriott, 1992). These expected patterns are clearly reflected in Figures 3, 4 and 5, with the highest rates of deposition and percentage of coarse material occurring close to the channel. In such regions, deposition rates estimated from both Cs-137 and Pb-210 exceed 0·5g cm^{-2} a^{-1} and the particle size distribution shows over 30 per cent of the material to be greater than 63 μm in diameter. Maximum deposition occurs on the left bank, upstream of the complex double meander, while away from near-channel areas deposition rates are lower and the material is almost wholly smaller than 63 μm. Figures 3,

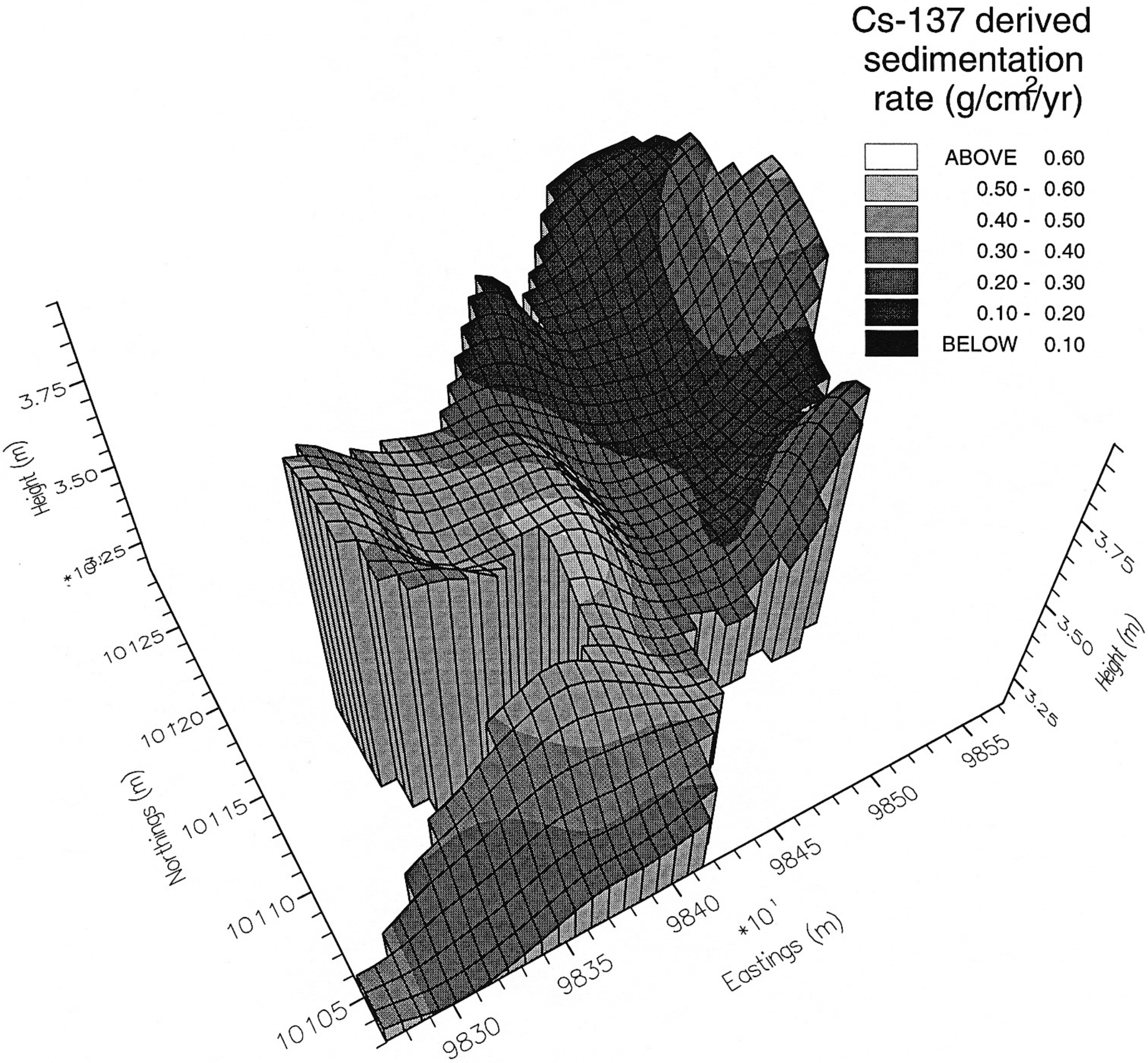


Figure 3. Cs-137 derived, 40 year averaged sedimentation rates interpolated to the mesh nodal points and overlaid onto the reach topography

4 and 5 also show that the highest medium-term sedimentation rates are spatially correlated with the highest topography on the surveyed floodplain, in this case the channel banks. The distribution of fine particles over the domain (Figure 5) clearly shows that the zones of highest percentage fines are located in the lowest regions, and which, on the basis of the above discussion, are presumably associated with ponding and low velocities. These results tie in well with those of a previous study by Walling *et al.* (1992) of medium-term sedimentation rates at this location. This study concluded that over such timescales scour was unlikely to be a significant process. It was also observed that the maximum deposition over the medium term occurred in regions close to the channel, and that deposition was preferentially associated with these regions, as well as situations where the local microtopography caused sediment to move to low ponded areas of the floodplain.

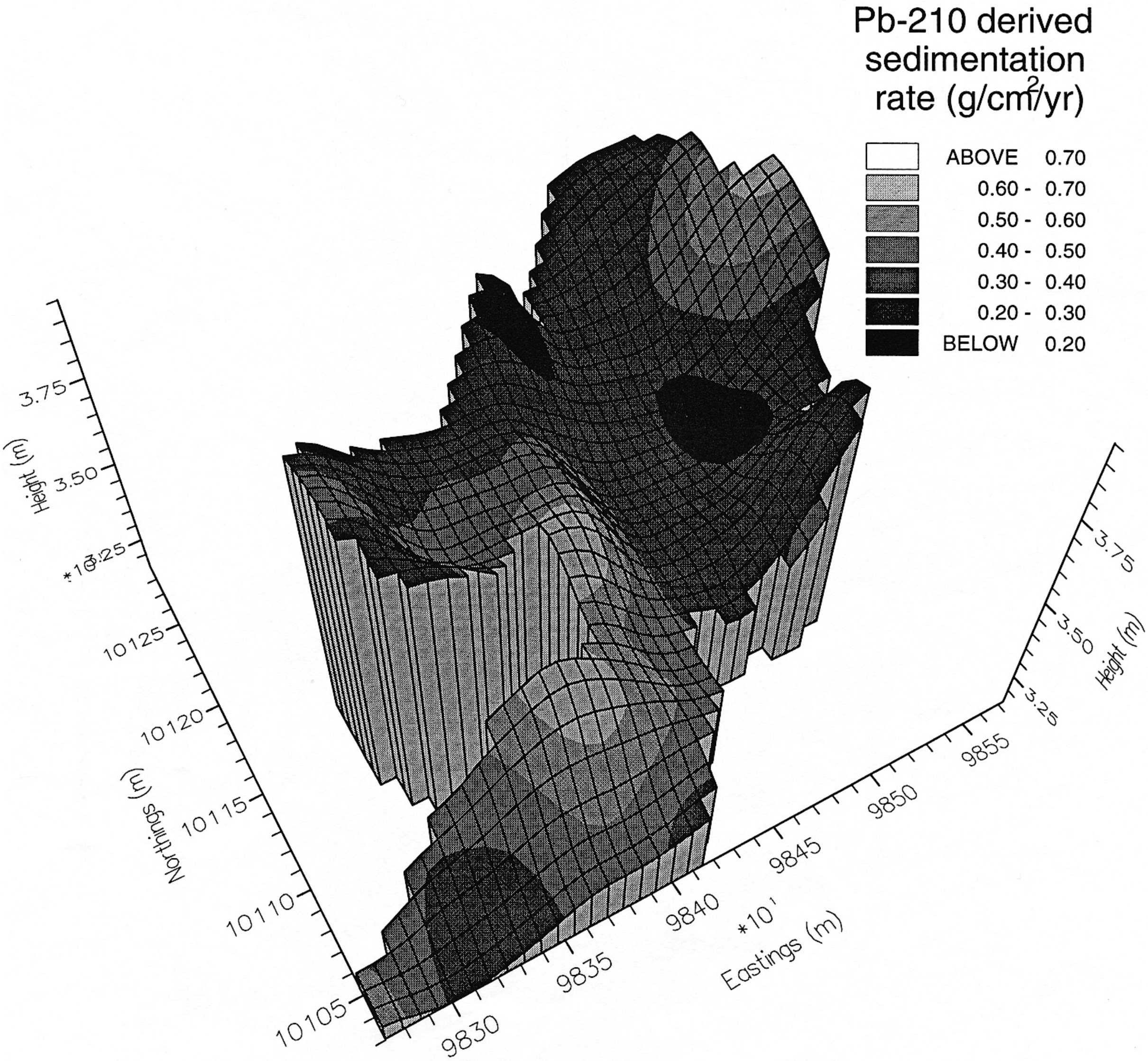


Figure 4. Pb-210 derived, 100 year averaged sedimentation rates interpolated to the mesh nodal points and overlaid onto the reach topography

Given that the results of the radionuclide inventories undertaken by the current study seem consistent with physical theory and previous observations, we can be reasonably confident that the data set gives a realistic representation of the local depositional environment which we can attempt to interpret in terms of the modelled hydraulics. This is given in Figure 6 where we show water depth and velocity vector patterns over the study zone at five stages during the event. Specifically Figure 6a–e gives a snapshot of the flood hydraulics at the start, rising limb, peak discharge, falling limb and end of the simulation period. Figure 6 shows that the region experiences a highly complex velocity regime for a 1 in 12 year flood event. In a two-dimensional simulation, Figure 6c shows that there is a time where a net velocity reversal occurs as the meander bend becomes swamped. The density and direction of velocity vectors in

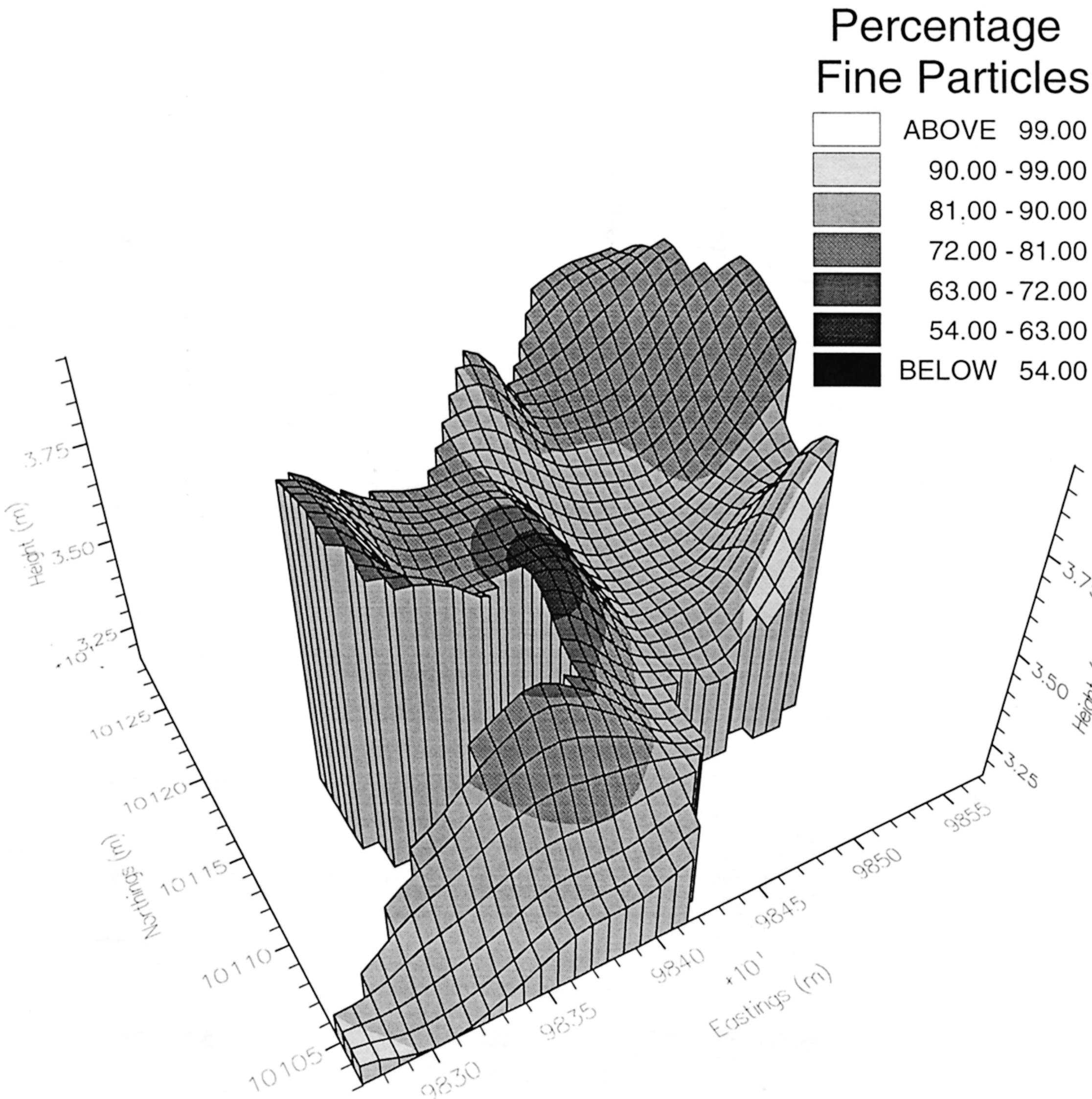


Figure 5. Surveyed distribution of percentage fine particles derived from analysis of surface sediment from the floodplain rates interpolated to the mesh nodal points and overlaid onto the reach topography

Figure 6c show the likelihood of erosion at the point of the meander bend during peak flow for a flood of this magnitude. The development of the hydraulics in this region also reveals a strong turbulent interaction between floodplain and channel flows. This is represented by the complex nature of the velocity vectors at the point of the meander bend during the rising stage (Figure 6b), and, more significantly, for the longer duration falling stage of the flood (Figure 6d). At this stage of the flood, the channel will also have a greater capacity for carrying coarse sediment.

The pattern of fine sediment deposition is clearly well represented in the model data, with the simulated inundation patterns at the tail end of the event (see Figure 6e) matching the observed regions

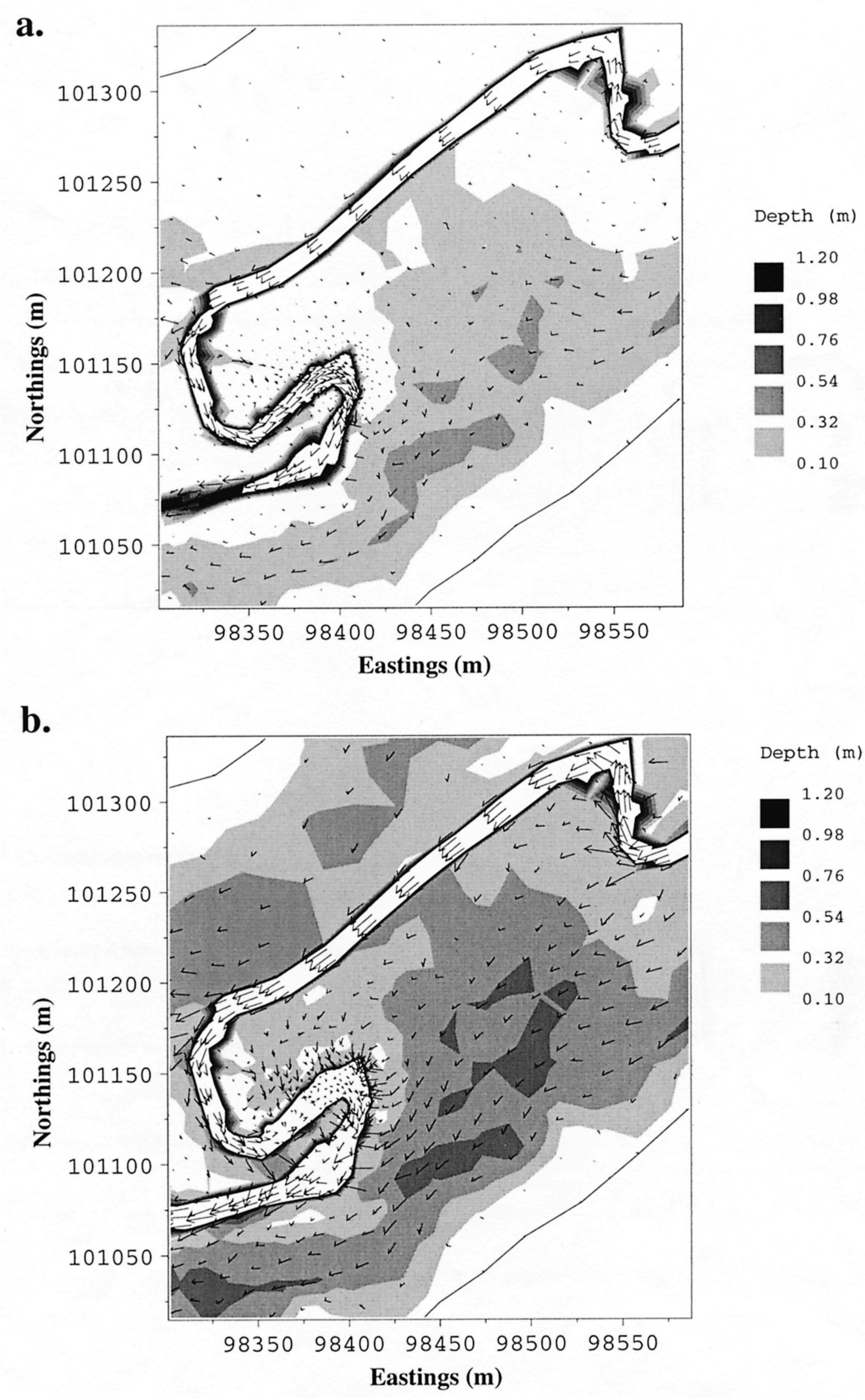
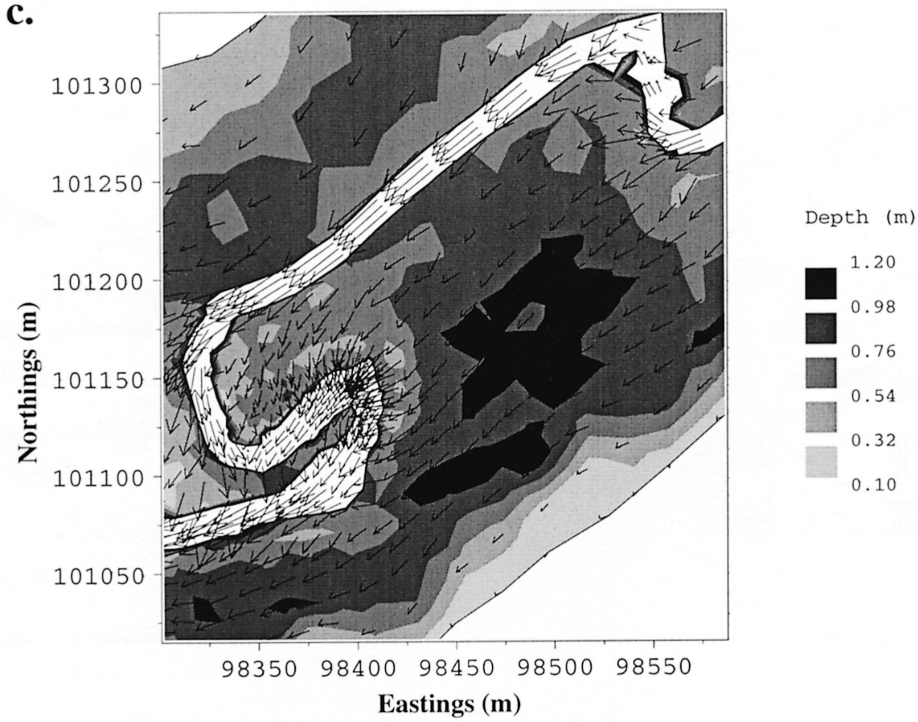


Figure 6. Predicted velocity vectors and inundation depths, shown over the surveyed study zone of interest, for (a) start of event, (b) rising limb, (c) peak discharge, (d) falling limb and (e) end of event



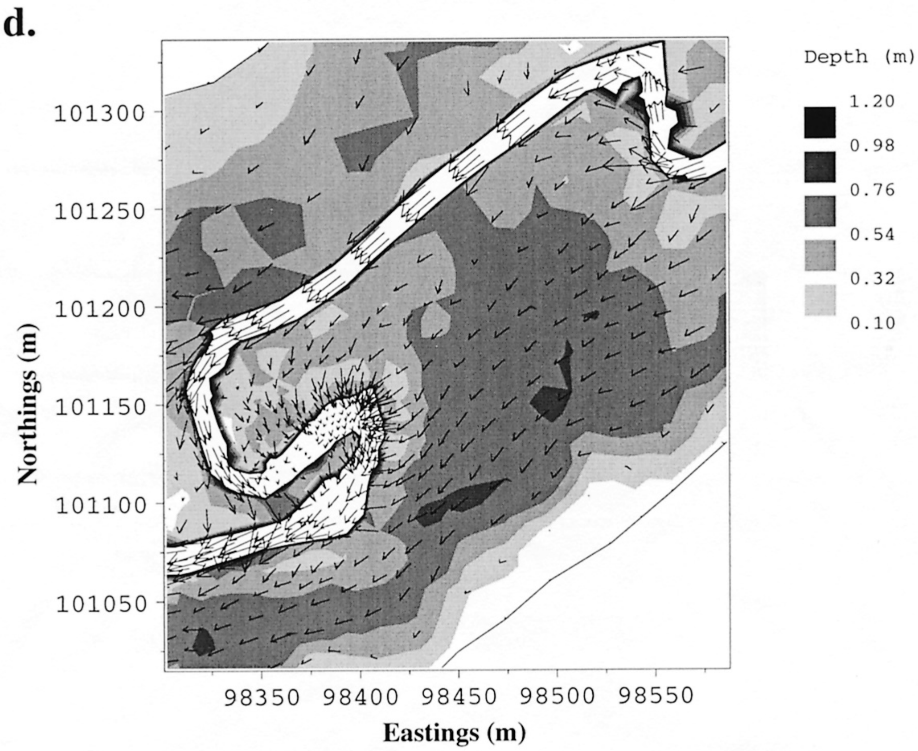


Figure 6. – continued

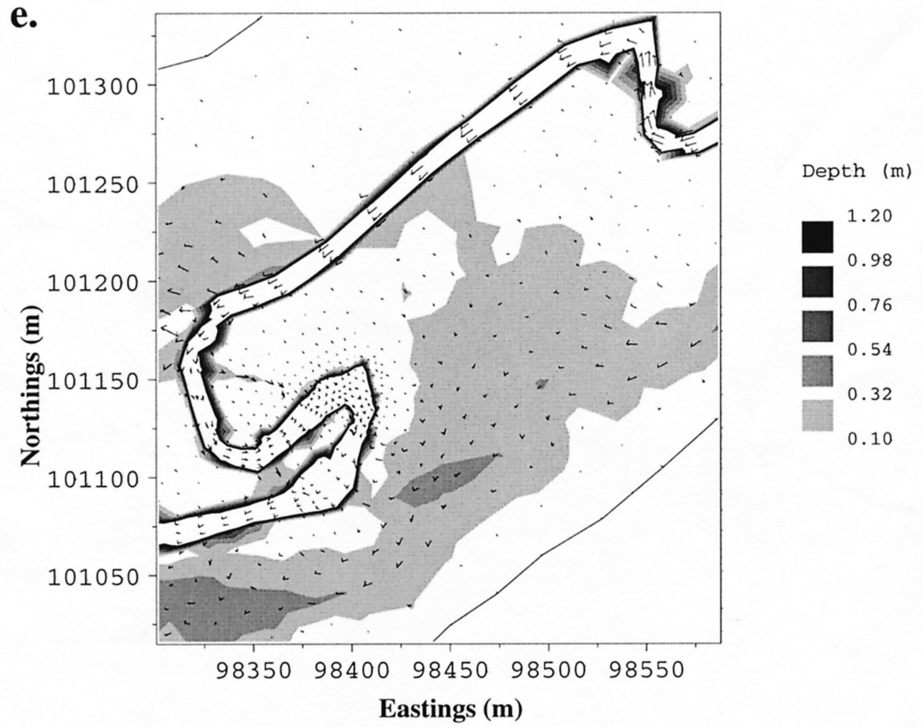


Figure 6. – continued

of highest fine sediment content. This is as one would expect if this fraction of the particle size distribution is to a greater extent hydraulically controlled. Walling *et al.* (1992) concluded that this pattern conformed to the concept of transfer of the sediment from the channel to the floodplain by turbulent diffusion as proposed by Allen (1985) and James (1985). Indeed, here the amount of deposition reflects the carrying capacity, and the observed grain size reflects the competence of the flow during the deposition period. Thus, the finer sediments remain in suspension until they reach the lower, low-flow regions of the floodplain, with the importance of microtopography in diverting sediment from the channel to the floodplain (as proposed by Walling *et al.*, 1992) being clearly seen in Figure 6e.

The pattern of coarse sediment depositon, with its inherent possibility of being affected by availability, is, however, more difficult to explain. On a positive note, the model does largely predict a velocity gradient from channel to floodplain flow and the areas of maximum deposition determined from the sedimentological inventory are coincident with areas of highest predicted floodplain velocity. Moreover, this occurs in near-channel regions as one would expect from physical principles. Despite this, two problems exist to complicate the interpretation: a lack of resolution commensurate to known processes in near-channel areas, and the influence of river meandering on the velocity vector pattern. Although the finite element method confers a number of advantages over alternative numerical schemes (e.g. finite difference (Nicholas and Walling, 1995)) in terms of the representation of a channel meandering within a wider floodplain belt (Samuels, 1985) due to its ability to vary the mesh resolution in areas of steep process gradients, current computational constraints necessitate a compromise as to where this model resolution is best 'used'. To represent the turbulent eddies observed (e.g. Sellin, 1964; Sellin and Willets, 1996) at the interface between the main channel and floodplain in compound channel flow would require element sizes in the near-channel region of significantly less than the length scale of these features

(< 1m). This is not currently feasible for the reach-scale simulations with which we are here concerned without oversimplifying the representation of floodplain topography over the rest of the domain. Whilst near-channel hydraulics can only be represented in a relatively simplified fashion, the impact of the meandering and the near-channel velocity vector patterns can be clearly seen in Figure 6. Here, over the areas of highest sediment deposition velocities are actually directed into the channel as there is a strong cross-floodplain flow stream resulting from spillage of water from the apex of an upstream meander. Thus in the absence of a well-developed channel/floodplain shear layer in the model, the velocity vector pattern cannot explain the observed deposition pattern in this region. A number of other such anomalies occur in near-channel areas including zones, such as on the inside loop of the double meander at the lower end of the reach where sedimentation is high yet velocities are low.

Such discrepancies are perhaps not surprising and should not be seen as condemning the approach to hydraulic modelling taken here. Rather, it suggests that hydraulic processes alone are not sufficient to explain observed sedimentation patterns, yet as two-dimensional finite element hydraulic models do explain a proportion of the sedimentological data they may be an appropriate vehicle for future research into reach-scale processes. Clearly, there are significant issues here to consider in future studies of hydraulic processes including the need to pay detailed attention to coupling in-bank and out-of-bank flow and the three-dimensional, transient nature of the flow structure in this complex region (e.g. Sellin and Willetts, 1996). In part this will be driven by complex topography and may force a questioning of some of the assumptions of the Shallow Water equations in order to be able to derive an appropriate solution.

To quantify the strength of the relationship between floodplain sediment deposition determined using radionuclide dating and hydraulics simulated with a two-dimensional finite element model operating at the current maximum feasible resolution, a series of scatter plots were examined. These are given in Figure 7a–c and show the relationship between scalar velocity at each of the 219 nodal points for a single time during the flood and the sedimentological data shown in Figures 3, 4 and 5, respectively. The hydraulic patterns on the falling limb of the hydrograph (Figure 6d) were initially chosen in order to capture the influence of low-velocity ponded water on the deposition of fine sediments. Whilst, ultimately, a full investigation of the time history of hydraulic patterns would seem essential to account for both the integrated velocity over the event and the possibility of reworking of deposited sediment, this would seem to be beyond the scope of the present paper. Depth-averaged velocity was therefore selected as a key hydraulic variable influencing the patterns of sediment deposition in order to undertake a preliminary analysis. Through examination of the spatial variability of nodal depth-averaged velocity vectors, it should be possible to gain some indication of the likely spatial distribution of sedimentation rates. Although bed shear stress was another available hydraulic variable, it was considered more important for sediment transport rather than sedimentation. In general terms, areas closer to the channel will tend to have higher velocities. Hence, there will be a greater transfer of sediment from the channel. Higher velocities also imply a more turbulent regime, thus resulting in higher sediment concentrations and the transport of coarser particles. Velocity fields also provide a general assessment of transfer of sediment from the channel to the floodplain. As one would expect, the scatter in these relationships is high, yet some general trends are emergent. There is a weak, positive relationship between Cs-137 and Pb-210 derived sedimentation rates and scalar velocity, with a degree of clustering in the Cs-137 data at low sedimentation rates. The scalar velocity versus percentage fines plot shows this clustering much more clearly and, as expected, shows a weak negative relationship between particle size and scalar velocity. This confirms the general view derived from a comparison of Figures 3–6 that, on the whole, the model better explains the distribution of the hydraulically controlled fine sediment. The scatter plots also indicate that whilst hydraulics are the driving force behind all sediment transport, a consideration of these forces alone only permits a partial insight into the processes operating. Further investigation will necessitate examination in more detail of both the hydraulics and the integration of these driving forces with sediment transport simulations.

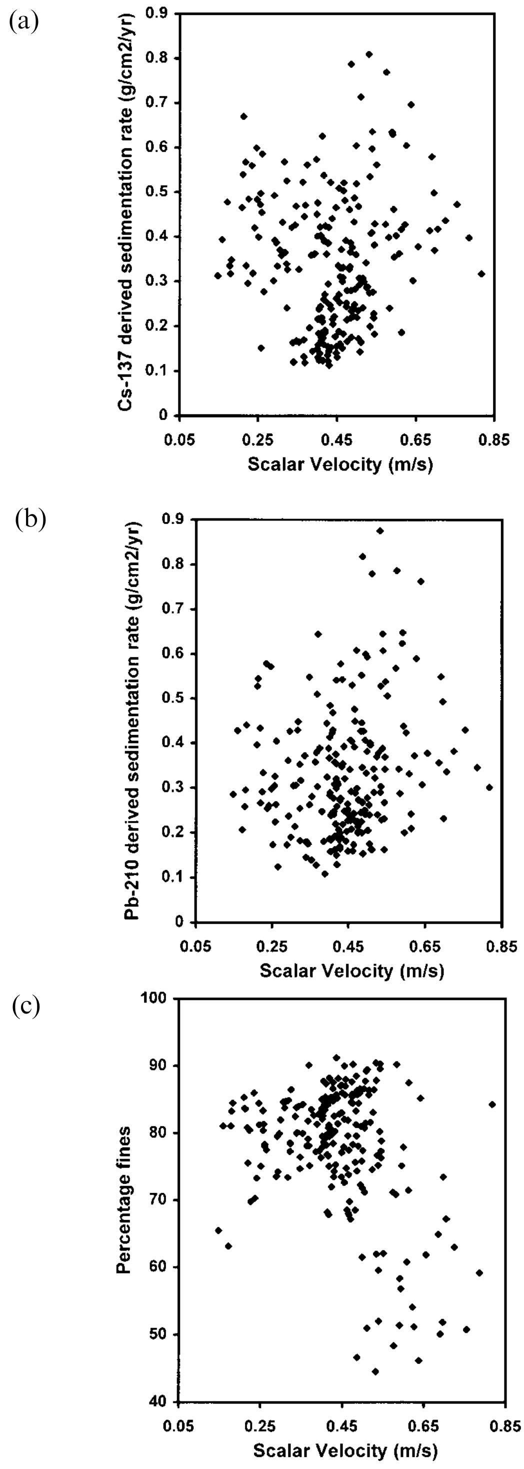


Figure 7. Scatter plots of scalar velocity at the 219 model nodes falling within the radionuclide study area during the falling limb of the flood hydrograph (Figure 6d) versus: (a) the Cs-137 derived, 40 year averaged sedimentation rates interpolated to the mesh nodal points; (b) the Pb-210 derived, 100 year averaged sedimentation rates interpolated to the mesh nodal points; and (c) the percentage fine particles derived from analysis of surface sediment from the floodplain interpolated to the mesh nodal points

DISCUSSION

A visualization of the complex development of inundation depths and flow velocities, and their coupling with observed medium-term sedimentation rates, was considered to provide a clearer insight into the processes involved, while at the same time pointing to ways in which the hydraulics can be better represented. The next logical step is the integration of a sediment transport model with the hydraulics results for the purpose of understanding the contemporary spatial patterns of deposition and erosion. Only after a thorough spatial calibration of the modelled flow parameters, and with an accurate representation of the suspended-sediment characteristics, is the integration of a sediment transport model considered a valuable development. The work reported here, therefore, is an essential first step.

A better understanding and model representation of the complex interaction between floodplain and channel flows is thus seen to be fundamental to the modelling of contemporary spatial variability in rates and distributions of sediments deposited near the channel. The spatial distribution of depth-averaged velocity (at peak flood) predicted by the model has been shown to connect with the patterns of deposition averaged over the medium term. With the labour-intensive nature of the field sampling and laboratory programmes required to generate Cs-137 and Pb-210 derived sedimentation rates over the spatial scale, it is also clear that hydraulic modelling has the potential, with support from Cs-137 and Pb-210 results, to improve the understanding of contemporary rates of floodplain deposition and erosion at the reach scale. With developments in the solution of the Shallow Water equations over regions of complex topography, and the inclusion of more realistic turbulence modelling, the model refinements suggested below should allow a more accurate representation of the floodplain hydraulics, sanctioning the coupling of a sediment transport model, and ultimately leading to the capacity to model the medium-term geomorphological development of the floodplain.

It is important to note that even with the limitations inherent in the model set-up, the two-dimensional hydraulic modelling of floodplain flow characteristics has been shown to reflect the observed relative distribution of sediment size and medium-term sedimentation rates. The representation of the turbulent interaction between floodplain and channel flows has been shown to be significant in that this represents the most dynamic region of the floodplain.

In proceeding to a more fully integrated model of floodplain development over the medium term, one must consider the ultimate goal, which must be a full understanding of the physics driving floodplain morphodynamics. Ideally, the simulation of successive flood events with the resulting deposition and erosion forming the new topography for the next event would lead to predictions of floodplain development. In reality, the suspended-sediment concentrations for successive flood events are determined by factors upstream, and are not simply related to the bulk flow characteristics. In progressing towards a model of medium-term floodplain development, an integrated model is seen as a possible solution. Cs-137 and Pb-210 derived averaged sedimentation rates can provide information on the sediment characteristics of the flows over these periods, as does core information on historical grain size distributions. Floodplain hydraulics are driven by the topography which is in turn driven by the deposition and erosion from the previous event. By starting with a historical topography derived from Cs-137 and Pb-210 measurements, with information on the suspended-sediment grain size composition derived from core samples, and with sufficient computer power, an attempt could be made to model the development of the floodplain. It must be realized that this would represent an ambitious undertaking, only realizable with state-of-the-art techniques in hydraulic modelling and medium-term sedimentation rate determinations. Such a validated model of medium-term floodplain development would represent a major advance in the ability to simulate landscape change.

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